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The impact of changes in the weather on the surface temperatures of Lake Windermere (UK) and Lough Feeagh (Ireland)

GLEN GEORGE[1], DIANE HEWITT[2], ELEANOR JENNINGS[3], NORMAN ALLOTT[3] & PHILIP McGINNITY[4]

1 *CEH Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK*
dgg@ceh.ac.uk

2 *Freshwater Biological Association, The Ferry House, Far Sawrey, Ambleside, Cumbria LA22 OLP, UK*

3 *Trinity College, College Green, Dublin 2, Ireland*

4 *Marine Institute, Newport, County Mayo, Ireland*

Abstract The surface temperatures of Lake Windermere (UK) and Lough Feeagh (Ireland) have been recorded every day since 1960. Here, we examine the factors influencing these measurements and their associated weekly variability. At both sites there was a progressive increase in the measured temperature, but the rate of increase was very much greater in Lake Windermere. The variance of the Lake Windermere temperatures was negatively correlated with the cloud cover, but there was no corresponding relationship in Lough Feeagh. Comparisons with the Lamb system of weather classification showed that the lake temperatures were closely correlated with these synoptic conditions. The highest winter temperatures were recorded during "westerly" conditions and the highest summer temperatures under "southerly" conditions. The most striking difference between the lakes was their response to cold winters and windy summers. Such results demonstrate that lakes that are topographically different "filter" the imposed climate signal in subtly different ways.

Key words climate change; Ireland; lake temperatures; UK; weather patterns

INTRODUCTION

Year-to-year changes in the weather have a major effect on the thermal characteristics of lakes (George, 1989; George *et al.*, 2004). Changes in the air temperature and cloud cover regulate the flux of heat across the air–water interface whilst variations in the wind speed influence the vertical dispersion of heat. Lakes thus behave as integrators of the local weather and can even amplify very weak meteorological signals (George & Harris, 1985; George & Taylor, 1995). Very little attention has hitherto been paid to the way in which lakes respond to short-term changes in the weather. Climatologists have devised a number of different ways to quantify these changes. Some, such as the North Atlantic Oscillation Index (Hurrell, 1995), are based on regional-scale gradients in the atmospheric pressure. Others, such as those devised by Lamb (1972), are based on the detailed analysis of daily weather maps. Here, we use the system devised by Lamb for the British Isles to explore the impact of long-term changes in the weather on the surface temperatures of two deep, thermally stratified lakes.

There are very few long-term records of the day-to-day variations in the surface temperature of a lake. Most long-term studies rely on measurements taken at weekly or fortnightly intervals. Several automatic monitoring stations have recently been established in Europe (Rouen *et al*., 2000) but these records are too short for systematic analysis. In this paper, we analyse some long-term records of the variations in the surface temperature of Lake Windermere in the UK and Lough Feeagh in Ireland. Both lakes are situated on the Atlantic coast and the measurements cover a 35–40 year period that extends from the early 1960s to the late 1990s.

DESCRIPTION OF SITES AND METHODS

Windermere, the largest lake in the English Lake District, covers an area of 8.1 km^2 and has a maximum depth of 60 m. It lies in a relatively sheltered valley (54º22′N; 2º56′W) and is divided into two basins by a large island. The surface temperatures were measured in a sheltered bay using a mercury thermometer with a resolution of 0.1°C. All measurements were taken in early morning (*c*. 08:30 hours GMT) to minimize the effects of near-surface heating. Lough Feeagh is a trough-like basin situated on the shores of Clew Bay in the west of Ireland (53°50′N; 9°35′W). It has a surface area of 3.9 km^2 and a maximum depth of 45 m. The surface temperatures were recorded by a Negretti system installed on the shore near the main outflow. The readings used were recorded at 06.00 h GMT and the nominal resolution of the chart was 0.1°C. The raw data from both sites was organized into a days *vs* years matrix and averages and standard deviations calculated for each week in each year. There were few breaks in the records, but weekend measurements at Lake Windermere were discontinued in the 1990s. Where measurements were not available for the full week, the means and standard deviations were calculated for the documented five days.

The variations in the local weather

At Lake Windermere, meteorological data were acquired from two weather stations in the village of Ambleside (54º24′N; 2º57′W). The first station was in operation from 1960 to 1974 and the second from 1971 to 2000. Here, we have combined the results to form a harmonized time-series that extends from January 1960 to December 2000. The average air temperature was calculated from the daily minimum and maximum and the cloud cover estimated by visual observation. At Lough Feeagh, meteorological data was acquired from a station located about 50 km away, near the town of Belmullet (54º13′N; 10º0′W). Here, all measurements were taken at hourly intervals by an observer stationed on site.

The variations in the regional weather types

The Lamb classification was originally based on a subjective analysis of daily weather charts but is now based on a multivariate analysis of the pressure gradients around the British Isles (Jones *et al*., 1993). The classification contains eight directional types, two non-directional types and an unclassified category. The directional types (N, NE, E, SE, S, SW, W and NW) are defined according to the general direction of the air flow. The non-directional types (A – anticyclonic and C – cyclonic) occur when high or low pressures systems are dominant. Table 1 shows the seasonal frequencies of the dominant circulation types as listed by Kelly *et al*. (1997).

The main circulation types are the westerly, the anticyclonic, the cyclonic and the northerly. There are no major differences in the seasonal distribution of these categories but westerly conditions are more common in winter. Here, we relate the seasonal variations in the lake temperatures and their variability to the changing frequency of westerly and anti-cyclonic conditions. Records of the week-to-week variation in these weather types were abstracted from a web page maintained by the Climate Research Unit (www.cru.uea.ac.uk) and then correlated with the lake temperature measurements. In this way, we could relate both the seasonal variation in the surface temperature of the lakes and their weekly variance to the changing frequency of the selected weather types.

Table 1 The frequency (%) of the dominant Lamb weather types between 1861 and 1990 (from Kelly *et al*., 1997).

Lamb Weather Type	Winter	Spring	Summer	Autumn
Westerly (W)	23.0	12.3	17.9	19.7
Anticyclonic (A)	16.1	17.3	18.9	18.9
Cyclonic (C)	10.7	12.0	16.1	12.1
Northerly (N)	3.3	5.6	4.8	4.6

RESULTS

The seasonal variation in the surface temperature

Figure 1 shows the average week-to-week variation in the surface temperature of Lake Windermere and Lough Feeagh.

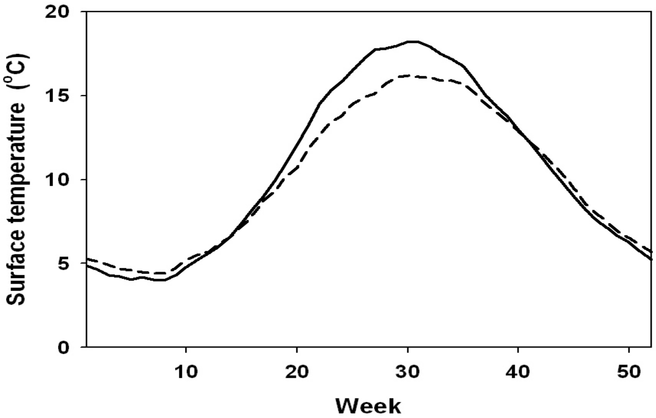

Fig. 1 The seasonal variation in the average surface temperature of Lake Windermere (—) and Lough Feeagh (- -).

The seasonal variations recorded at the two sites were very similar but the summer temperatures in Lake Windermere were about 2°C higher than that those in Lough Feeagh. The main factor influencing the surface temperature of a deep lake is the duration and intensity of thermal of stratification. The timing of the onset of stratification was very similar at the two sites but the autumn overturn was a few weeks earlier in Lough Feeagh. The relative exposure of the two sites also has an effect on the stability of the thermocline. The average depth of the thermocline in the two lakes is about 13 m but the temperature gradients that develop in Lake Windermere are steeper than those reported from Lough Feeagh.

The long-term change in the surface temperature

Figures 2(a) and (b) show the long-term change in the surface temperature of Lake Windermere and Lough Feeagh. The points show the annual means, the lines the three-point running means and the fitted linear regressions the trends. In both lakes, there was a sustained increase in the average surface temperature but the rate of increase was greater in Lake Windermere than in Lough Feeagh. At Lake Windermere, the temperature increased by 1.4°C between 1960 and 2000. At Lough Feeagh, the increase was only 0.7°C between 1960 and 1997. The other difference between the lakes was the pattern of change experienced in the 1990s. In Lake Windermere, a rising trend was still evident, but the temperature variations in Lough Feeagh were then more irregular.

Figures 2(c) and (d) show the long-term change in the variability of the temperature measurements from Windermere and Lough Feeagh. The points show the annual means of the standard deviations and the lines the three-point running means. The range of variation and the pattern of change were strikingly different at the two sites. In Lake Windermere (Fig. 2(c)), the standard deviations increased in the 1960s and 1970s before declining in the 1980s and 1990s. In Lough Feeagh, the standard deviations were consistently lower and remained more or less constant until they increased in the 1990s.

Factors influencing the surface temperatures and their variability

In lakes that are free of ice, the surface temperature is closely correlated with the local air temperature. Figures 3(a) and (b) show the relationship between the surface temperature and the air temperature at Lake Windermere and Lough Feeagh. At Lake Windermere, there was a very strong positive correlation between the two variables ($r = 0.93$, $p < 0.001$). At Lough Feeagh, the correlation with the Belmullet air temperatures was lower ($r = 0.72$, $p < 0.001$).. A number of factors can influence the surface temperature of a lake but the most important are the wind speed and the cloud cover. Since there were no wind speed measurements for the sites, our analyses were confined to cloud cover. Figures 3(c) and (b) show the relationship between the average standard deviation of the temperature measurements at Lake Windermere and Lough Feeagh and the average cloud cover at the meteorological stations. At Lake Windermere (Fig. 3(c)), there was a significant negative correlation between the two variables but the variations at Lough Feeagh were not correlated with the cloud cover.

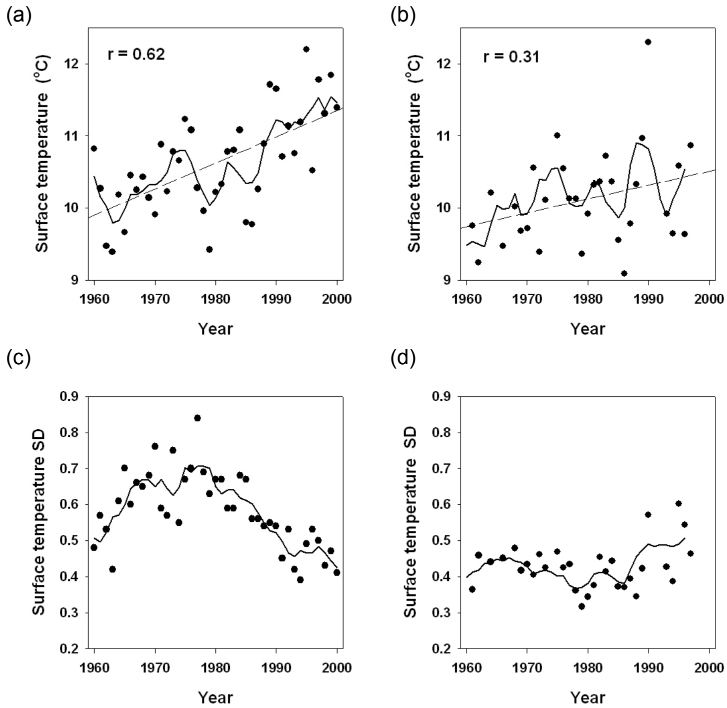

Fig. 2 The long-term trend in the surface temperature of (a) Lake Windermere and (b) Loch Feeagh. The long-term trend in the variability (standard deviation) of the temperature measurements from (c) Lake Windermere and (d) Lough Feeagh. The solid lines are the three-point running means and the broken lines fitted regressions.

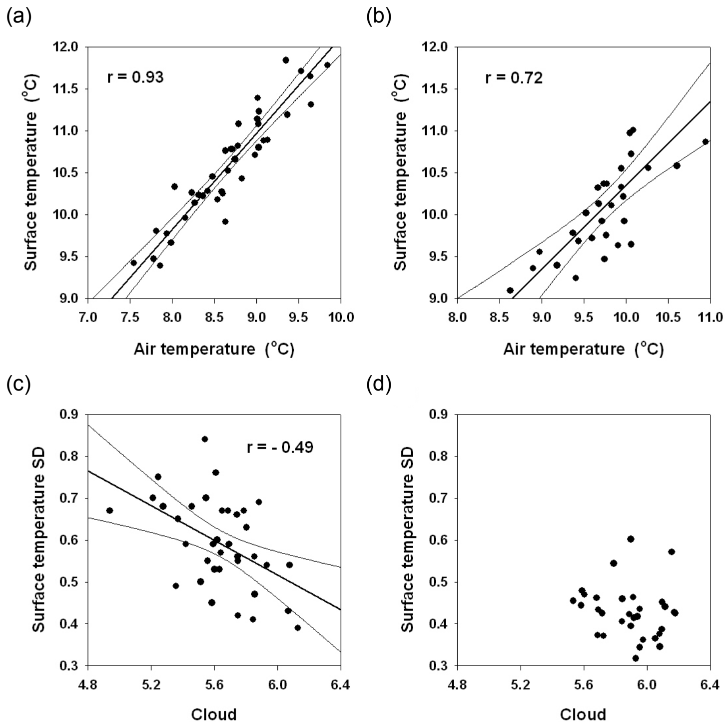

Fig. 3 The relationship between the average temperature of (a) Lake Windermere and (b) Lough Feeagh and the local air temperature. The relationship between the variability (standard deviation) of the temperature measurements in (c) Lake Windermere and (d) Lough Feeagh and the local cloud cover. The heavy lines show the fitted regressions and the light lines the 95% confidence intervals.

The influence of westerly weather on the surface temperature

This weather type is typically associated with higher winds along the western seaboard and milder, wetter conditions during the winter. Figures 4(a) and (b) show the effect that this weather type had on the surface temperatures of Lake Windermere and Lough Feeagh. The points show the correlation between the surface temperature and the number of westerly days recorded in each week of the year. The solid line shows the three-point running mean and the broken lines the significance levels for the correlation coefficients. The seasonal variations in these correlations were very similar at the two sites. At both sites, an increase in the number of westerly days was associated with higher surface temperatures in the winter and lower surface temperatures during the summer.

Figures 4(c) and (d) show the effect that westerly weather had on the variability of the temperature measurements. In Lake Windermere (Fig. 4(c)), most of the correlations were low but five significantly negative relationships were recorded during the winter. The pattern in Lough Feeagh (Fig. 4(d)) was very different. Here, the correlations were more variable and five significantly negative relationships were recorded during the summer. The most likely explanation for these differences are the colder winters experienced in Windermere and the windier summers recorded in the west of Ireland. During the period of study, the average winter air temperatures recorded at Ambleside were 2.7°C lower those recorded at Bellmullet. In contrast, the average summer wind speeds at Belmullet were 2.5 m s^{-1} higher than those recorded at Ambleside. Cold winters can result in more variable surface temperatures if there are day-to-day variations in the rate of convective cooling. Windy summers can have the same effect by cooling the lake surface and entraining colder water from deeper layers.

The influence of anticyclonic conditions on the surface temperature

Anticyclonic conditions are typically associated with cold weather during the winter and with warm weather during the summer. Figures 5(a) and (b) show the effect that this weather type had on the surface temperatures of Lake Windermere and Lough Feeagh. The points show the correlation between the surface temperature in a particular week and the number of anticyclonic days recorded over the same period. The solid line shows the three-point running mean and the broken lines the significance levels for the correlation coefficients. The seasonal variation in the correlations was very similar at the two sites. At both sites, the lowest winter and the highest summer temperatures were recorded when there was an increase in the number of anticyclonic days. Figures 5(c) and 4(d) show the effect that these anticyclonic conditions had on the variability of the temperature measurements. In Lake Windermere (Fig. 5(c)), the number of significant correlations were low but eight positive correlations were recorded during the summer. In Lough Feeagh (Fig. 5(d)), there were more significant correlations with 16 positive correlations being recorded during the summer. These differences are, almost certainly, a function of the very different wind regimes experiences at the two sites i.e. the cooling effects of short-term changes in the wind speed are more pronounce at Lough Feeagh than at Windermere.

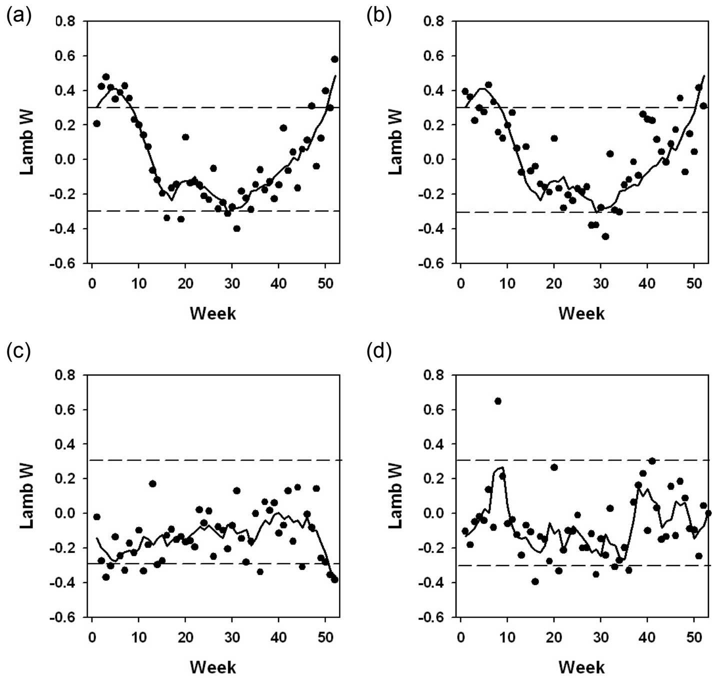

Fig. 4. The correlation between the weekly temperatures of (a) Lake Windermere and (b) Lough Feeagh and the frequency of westerly conditions. The correlation between the variability (standard deviation) of the weekly temperatures in (c) Windermere and (d) Lough Feeagh and the frequency of "westerly" conditions. The solid lines show the three-point running means and the broken lines the significance levels.

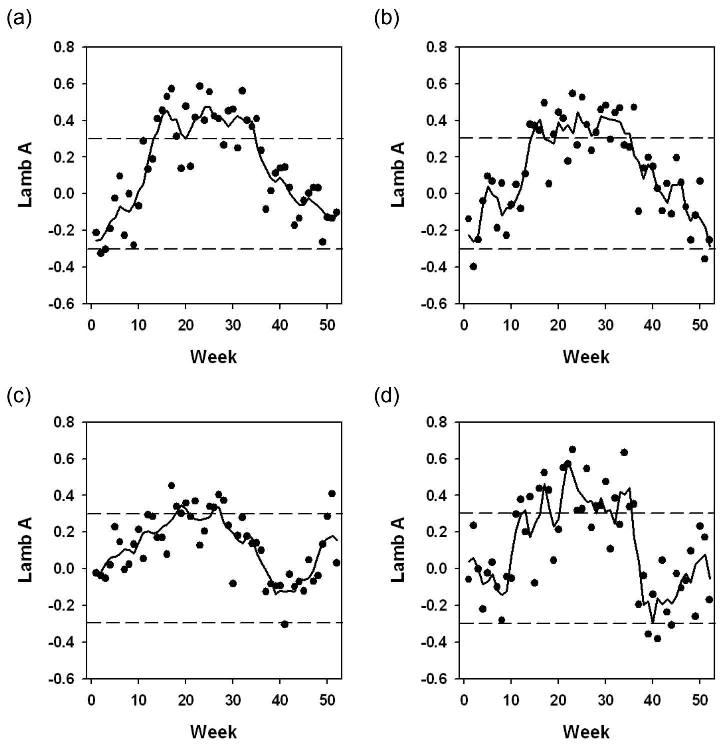

Fig. 5 The correlation between the weekly temperatures of (a) Lake Windermere and (b) Lough Feeagh and the frequency of anticyclonic conditions. The correlation between the variability (standard deviation) of the weekly temperatures from (c) Windermere and (d) Lough Feeagh and the frequency of anticyclonic conditions. The solid lines show the three-point running means and the broken lines the significance levels.

DISCUSSION

In this paper, we have compared the thermal responses of two lakes that are exposed to the same weather systems but are topographically rather different. Lake Windermere is a morphometrically complex basin situated in a sheltered valley about 20 km from the sea. Lough Feeagh is a trough-like basin situated in a more open location very close to the sea. The data assembled show that the surface temperature of both lakes increased during the period of study but the rate of increase was much greater in Lake Windermere. The most likely explanation for this difference is the exposed situation of Lough Feeagh and its greater sensitivity to wind-induced mixing. The frequency of severe gales over the British Isles has increased in recent years and there has also been an increase in the wave heights measured in coastal waters (UKCIP, 2002).

The weather-type analyses presented here demonstrate that the system of weather classification designed by Lamb for the British Isles also works for the west of Ireland. The observed correlations between the surface temperatures of the lakes and these synoptic categories were very similar at the two sites. There were, however, significant differences in the long-term trends and the short-term variations recorded at the two sites. The rate of warming was much greater at the more sheltered site but the day-to-day variations in the surface temperature were more pronounced at the exposed location. Such results demonstrate that lakes that are topographically different can "filter" the imposed climate signal in a subtly different way. At present, we know very little about these filtering effects but George (2006) has documented some striking inter-annual variations in two neighbouring English lakes. The "weather type" approach adopted here has the merit of quantifying these effects in synoptic terms using indices that can be related to regional-scale variations in the atmospheric circulation.

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